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Algorithm for Computing Monthly Averaged Inflow of Atlantic Water to the Norwegian Sea

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REPORT

AN ALGORITHM FOR COMPUTING MONTHLY AVERAGED INFLOW OF ATLANTIC WATER TO THE NORWEGIAN SEA

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SINTEF

REPORT

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TITLE

AN ALGORITHM FOR COMPUTING MONTHLY AVERAGED INFLOW OF ATLANTIC WATER TO THE NORWEGIAN SEA

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ABSTRACT

Monthly averaged inflows of Atlantic Water to the Norwegian Sea from September 1982 to August 1984 are estimated from sea level measurements at Harstad in Northern Norway. An algorithm calibrated to direct measurements at Stad to the south, taking into account air pressure and wind, reproduces nine months of field measurements at Shetland to within a standard deviation of 15 %. Based on indices from newer data and numerical modelling, it is concluded that annual seasonal variability may well be influenced by hemispherical thermodynamical driving, but monthly variability is driven primarily by dynamical processes that modulate the sea level in the NE Atlantic.

KEYWORDS	ENGLISH	NORWEGIAN
GROUP 1	Oceanography	Oseanografi

FOREWORD

The algorithm presented in this report was prepared for the North Norwegian Coastal Ecology Program MARE NOR under the auspices of the Norwegian Research Council for Science and the Humanities (NAVF) and supported by the Office of Naval Research under Grant N00014-90-J-1882. Work on the proof of a key assumption of coherency between currents at Shetland and Lofoten is still in progress at the termination of the project. Simultaneous current measurements at these locations for conclusive evidence have not been found. The analysis of data acquired for indirect indices is yet incomplete.

Theoretical arguments for the coherency of the barotropic flow along the shelf break rest on the conservation of potential vorticity. The basic idea is that sea level changes in the North Atlantic regulate the flow over the Shetland-Iceland Ridge and that these propagate to the right along the shelf break of the Norwegian Continental Shelf. Internal wave signals also propagate to the right, but at a slower speed. These signals are, however, faster than the adjustments due to topographic Rossby waves and, of course, faster than the currents themselves.

It is suggested that the water-level induced lateral spread off the shelf induces a longshore, shelf edge current in geostrophic balance with a lateral pressure gradient. This balance, which is the essence of the algorithm is expected to establish quickly after a rise in the sea level along the coast, and has some support in the sea level data. Recent numerical model work by Martinsen et al. (1992) shows that barotropic shelf edge currents are established in less than 2 weeks all along the shelf break following a sea level rise in the NE Atlantic. Likewise, some undocumented results from laboratory simulations of ocean currents on the central Norwegian Continental Shelf (Mc Climans and Larsen, 1988) revealed a fast decay when the source was shut down.

The tentative conclusions from these facts are that the annual signals may well be influenced by hemispherical thermodynamics, but that monthly variability is due primarily to dynamical processes affecting the sea level in the NE Atlantic. This has important consequences for evaluating the relative roles of global distributions of heat flux and winds on climate change.

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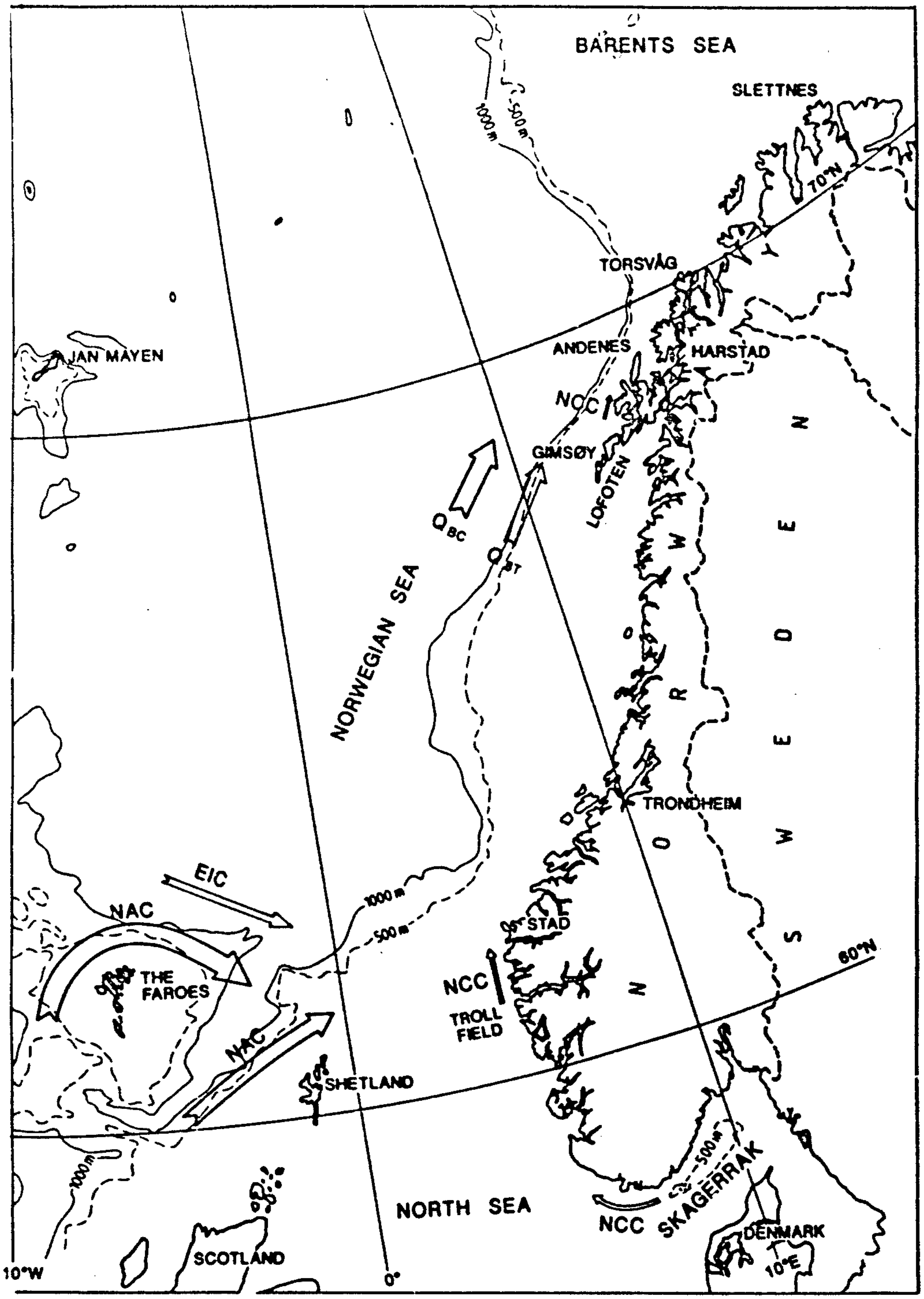
An Algorithm for Computing Monthly Averaged Inflow of Atlantic Water to the Norwegian Sea

INTRODUCTION

The inflow of warm Atlantic Water between Shetland and Iceland is vital to life on land and in the sea. WORTHINGTON (1970) computed the annual inflow of Atlantic Water to the Nordic seas to be ca 8 Sv based on the heat budget. Similar estimates are inferred by the work of MYSAK & SCHOTT (1977), McCARTNEY & TALLEY (1984), GOULD et al. (1985) and HANSEN (1986). The thermodynamics of atmospheric cooling and brine rejection during ice formation drive this system seasonally. GOULD et al. showed that monthly averages can vary from 4 to 12 Sv. This variability is important for forcing regional oceanographic models and, recently, McCLIMANS & NILSEN (1990) developed a diagnostic relation between the inflow and the resultant low frequency sea level changes at Andenes to force a model of the Barents Sea.(See map of Fig. 1.)

This idea is not new. CHRISTENSEN & RODRIGUEZ (1979), for example, computed geostrophic currents off Baja California this way. The present work is intended to show the steps taken to obtain a reasonably good algorithm for the Norwegian Atlantic Current (NAC).

The monthly variability is directly related to the synoptic weather patterns in the North Atlantic and the Nordic seas (JONSSON, 1991). Although the cause/effect relations are important for prognostic (forecasting) capabilities and are the essence of coupled global air-sea-ice models, we will limit the present work to an improved diagnostic algorithm for use in forcing regional oceanographic models of the continental margins of the Nordic seas.


BARENTS SEA
SLETTNES
1000 m
500 m
70°N
TORSVÅG
JAN MAYEN
ANDENES
HARSTAD
NCC
GIMSØY
LOFOTEN
Q_{BC}
Q_{BT}
NORWEGIAN SEA
SWEDEN
NORWAY
TRONDHEIM
EIC
NAC
1000 m
500 m
STAD
THE FAROES
NCC
TROLL FIELD
60°N
NAC
SHETLAND
1000 m
500 m
SKAGERRAK
NORTH SEA
NCC
DENMARK
SCOTLAND
10°W
0°
10°E

THE SIMPLE GEOSTROPHIC MODEL

The large time and space scales considered here justify the use of a simple geostrophic balance. The major factors affecting the low frequency (periods greater than 2 weeks) water level along the coast of Norway are ocean currents, air pressure, wind and land rising (sea level change), the latter being only important for analyzing data from different decades. PLAG (1988) estimates land rising in the Andenes region to be on the order of 2 mm/yr. In the present work processes contributing to less than 2 cm sea level variations are ignored. Thus computing ocean currents from low frequency water level changes requires meteorological data to account for air pressure and wind effects which greatly exceed 2 cm variability.

The geostrophic model is sketched in Fig. 2. The NAC is divided into two parts: the off-slope baroclinic transport and the barotropic transport at the shelf break (McCLIMANS & NILSEN, 1990). The near shore Norwegian Coastal Current (NCC) inside the shelf break current will be treated as a correction term. It depends on the outflow of fresh water from northern Europe, which is an independent forcing.

The quality of the data, considering the variability and errors involved do not warrent a more exact theory at this stage. Thus the baroclinic transport is estimated by the hydrographer's equation for

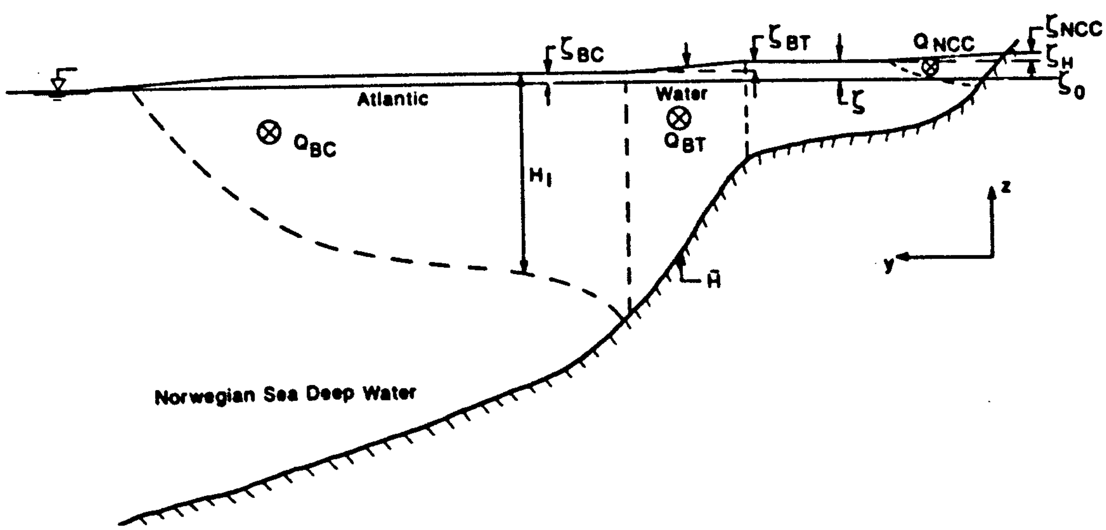


Fig. 2. A cross sectional sketch of the geostrophic flow.

the region off-slope

$$Q_{BC} = g'H_1{}^2/2f \tag{1}$$

where the reduced gravity g' is roughly 0.005 m/s^2 for almost all of the conditions reviewed, H_1 is the thickness of the upper layer in an equivalent 2-layer ocean with $g' = 0.005\ m/s^2$ and the Coriolis parameter $f = 1.35 \times 10^{-4}\ s^{-1}$ at the location of the tidal gauge.

The barotropic flow is concentrated on the shelf break (see e.g. MYSAK & SCHOTT, 1977). The horizontal pressure gradient ∇p is proportional to the long-slope velocity u

$$\frac{1}{\rho}\frac{\partial p}{\partial y} = -uf = g\frac{\partial z}{\partial y} \tag{2}$$

where ρ is density, g is the acceleration of gravity and z is the surface elevation. Integrating the velocity over the cross sectional area of the shelf break gives the barotropic transport

$$Q_{BT} = \frac{g\bar{H}}{f} z_{BT} \tag{3}$$

where $\bar{H}$ is the average depth of the core of the barotropic current and z_{BT} is the surface jump across the jet. According to the results of MYSAK & SCHOTT, $\bar{H} = 450$ m.

The equivalent surface elevation for the baroclinic flow can be estimated by assuming that the deeper water is at rest (consistent with eq. 1)

$$z_{BC} = g'/g\ H_1 \tag{4}$$

giving

$$Q_{BC} = g^2 z^2{}_{BC}/2g'f \qquad (5)$$

Since we measure $z = z_{BC} + z_{BT}$, the computation of the total transport $Q = Q_{BC} + Q_{BT}$ on the basis of z requires an additional constraint. The constraint chosen by McCLIMANS & NILSEN (1990) is based on the conjecture that the upstream topography divides the flow naturally into two proportional parts. From the direct measurements of MYSAK & SCHOTT (1977) this amounts to specifying

$$Q_{BT} = 3/8\ Q \qquad (6)$$

Thus, within the framework of geostrophic flow and the above estimated constants, the flow of Atlantic Water to the Nordic Seas can be estimated from water level measurements at Andenes according to the following inverse algorithm

$$z = Q/90 + Q^{1/2}/11 \qquad (7)$$

In (7) z has the units of m and Q has the units of Sv (Sv = 10^6 m^3/s). It should be further commented that this relation is purely diagnostic between z and Q, and that z is the elevation above a sea at rest.

WATER LEVEL MEASUREMENTS

The first attempt to develop an algorithm of this type, to obtain good boundary conditions for a laboratory model of the Barents Sea, utilized water level measurements at Andenes (Norwegian Hydrographic Survey) and nearby hydrographic data to obtain Q_{BC} (Inst. of Marine Research). Andenes was chosen because it was the closest water level station to the shelf break. The data from Andenes were, however, incomplete. Furthermore, the station has been out of function after a fire in 1987.

The present work was initiated to see if the Harstad water level station in the Andfjord system could be used as an alternative to Andenes(see Fig. 1). This station has a very good, long time series for statistical analysis. It was furthermore of interest to use a more reliable set of direct current measurements to estimate the accuracy of this type of algorithm. The earlier algorithm was estimated to have an accuracy of $\pm$ 30 %. This does not sound very good, but in terms of model forcing it should be noted that the monthly average Q was estimated to vary from 3 to 16 Sv within a period of 7 years, including large month to month variability.

The monthly averaged hourly values of water level at Harstad for the period September 1982 to August 1984 are given in Table 1 together with monthly averaged air pressure and wind components from Torsvåg (see map in Fig. 1) (Norwegian Meteorological Institute). The contribution of sea level rise for the Norwegian Coastal Current z_{NCC} is computed from the outflow of brackish water from the Skagerrak, derived from the computer model MAKRILLEN (STIGEBRANDT, 1984). Monthly sea level variations for the coastal current in the Skagerrak exceed our chosen noise level of 2 cm. This effect will be discussed later. The last column on the right in Table 1 is the adjusted sea level values z_H above the Harstad datum. The pressure adjustment is 1 cm/mb and the wind correction is $0.6(0.5W_E - 0.866W_N)|0.5W_E - 0.866W_N|$(cm).

The reasons for choosing 1982-1984 are many. From the earlier work (McCLIMANS & NILSEN, 1990) this was a period of exceptionally large winter inflows to the Barents Sea. The period was also used for other laboratory model simulations (McCLIMANS, 1985; McCLIMANS & NILSEN, 1991). Most important it is a period with several sets of current

Table 1. Water level at Harstad, relevant meteorological data from Torsvåg, computed water level rise for the NCC and corrected water level z_H.

Year	Month	Water level (cm)	Air pressure (mb)	Wind, W (m/s,N)	Wind, W (m/s,E)	z_{NCC} (cm)	z_H (cm)
1982	Aug					7.6	
	Sep	163.6	1003.7	-1.39	-0.98	10.0	167.6
	Oct	157.0	1010.5	-2.62	1.68	16.5	173.3
	Nov	178.8	994.9	-3.24	0.68	8.8	179.6
	Dec	177.[illegible]	991.8	-3.20	0.11	10.8	174.2
1983	Jan	186.7	986.9	-3.45	2.25	6.9	183.7
	Feb	152.6	1006.9	-2.30	-3.24	14.7	159.4
	Mar	155.8	1002.4	-2.21	0.24	14.1	160.7
	Apr	139.8	1011.0	-2.08	2.41	14.5	156.2
	May	142.4	1013.2	-1.61	1.34	13.6	158.2
	Jun	147.6	1011.5	-2.11	-1.53	11.6	159.8
	Jul	152.6	1010.4	-1.31	-0.54	10.8	163.4
	Aug	157.3	1006.2	-3.00	-2.55	10.0	164.6
	Sep	161.2	1004.2	-0.83	-0.20	10.1	165.6
	Oct	176.7	994.4	0.75	0.67	9.4	171.0
	Nov	175.9	999.8	1.58	0.01	11.2	174.6
	Dec	171.2	998.1	-1.39	0.61	11.4	170.7
1984	Jan	166.3	994.6	-3.39	2.67	12.3	171.8
	Feb	152.3	1008.9	-6.43	1.12	15.1	183.7
	Mar	141.7	1018.5	-1.54	1.13	16.1	162.4
	Apr	141.1	1013.7	-3.40	-0.06	11.3	159.9
	May	138.5	1013.1	-0.62	0.20	12.7	151.8
	Jun	142.6	1011.0	0.32	-0.53	11.2	153.4
	Jul	145.1	1009.7	0.86	-0.99	9.2	153.9
	Aug	144.4	1011.8	-1.01	-0.61	9.1	156.4

COMPUTING THE "SEA AT REST" LEVEL

The Harstad datum for water level measurements is below the normal spring low tide. Clearly this cannot be used in (7) to compute Q. The "sea at rest" level must be obtained by applying (7) to a good quality set of observed transports. Here, the results of MYSAK & SCHOTT (1977), upon which most of this work is based, will be used to calibrate "the ocean at rest". The value of Q for the period 6 Aug - 4 Sep 1969 is estimated to be $Q = Q_{BC} + Q_{BT} = 4.5$ Sv $+ 2.5$ Sv $= 7$ Sv from this data. The corresponding water level and meteorological measurements are 150.6 cm, 1016.8 mb, 1.05 m/s N and 0.52 m/s E. The pressure measurements were taken at Slettnes, to the east of Torsvåg.

Although land rising is estimated to be only 2 mm/yr during the interim, it is necessary to adjust the datum by 14 x 2 = 28 mm. The calibration for average sea level of no motion z_0 is, from (7)

$$z \equiv z_H - z_0 = 7/90 + 7^{1/2}/11 \qquad (8)$$

for which the elevations are given in units of m.

Applying the above corrections to the observed water level gives $z_H = 1.64$ m. From (8), then

$$z_0 = 1.64 - 0.08 - 0.24 = 1.32 \text{ m} \qquad (9)$$

This reference does not account for the effect of the NCC, which is estimated to be 10 cm for this August situation, so in reality the sea at rest is a decimeter lower. This does not enter into the geostrophic theory for the NAC, but variations in z_{NCC} are of course of interest for computing the proper z from observations of z_H.

COMPARISON WITH DIRECT MEASUREMENTS

One set of direct measurements was needed to calibrate the sea at rest. To see how well the algorithm behaves requires a more extensive set of transport measurements. Such a set is presented by GOULD et al. (1985). Transport measurements and computations of z from Table 1 and the left part of eq. 8 are presented in Table 2 for 9 months.

Table 2. Observed monthly averaged transport of Atlantic Water past Shetland and water level at Harstad above "sea at rest".

Year	Month	Q (Sv)	z (m)
1983	Sep	8.1	0.336
	Oct	8.0	0.390
	Nov	9.5	0.426
	Dec	7.3	0.387
1984	Jan	11.4	0.398
	Feb	12.6	0.517
	Mar	7.4	0.304
	Apr	6.4	0.279
	Aug	4.0	0.244

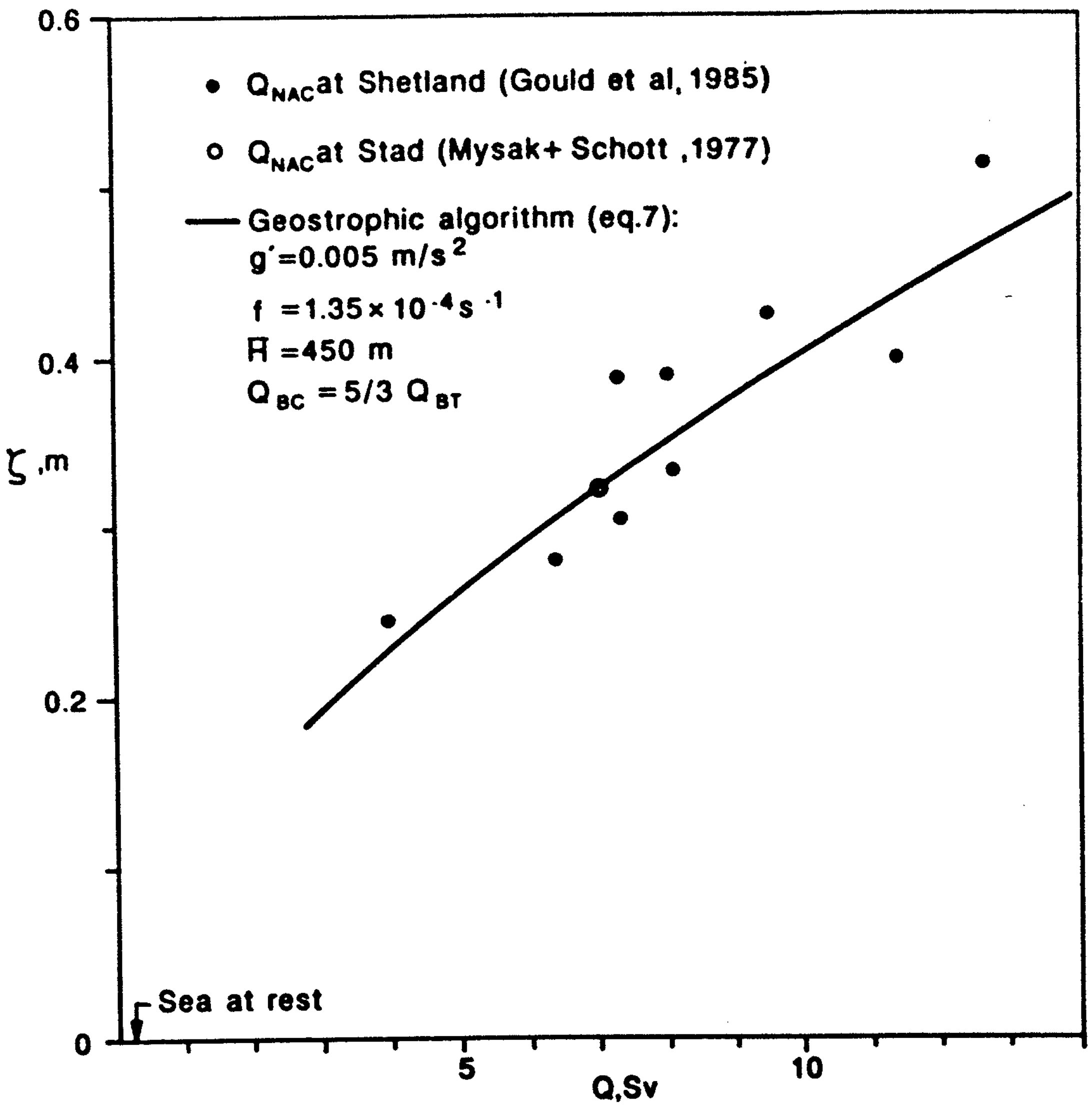
Although these data sets are separated by more than 1000 km along the Norwegian continental shelf break there is reason to believe that they are closely related, at least on a monthly time scale. The basin is primarily a flow-through channel for the Atlantic Water being pulled into the Arctic Ocean. The barotropic flow is forced along the slope so that continuity signals propagate rapidly from place to place (about one week for internal Kelvin waves). This time scale should not be confused with the much longer advection time scale for water properties. With an average cross section of 0.5x400 km^2 the average

past Andenes. DICKSON et al (1988) showed an even longer time of travel for the "Great Salinity Anomaly" of the seventies.

The variability of z_{NCC} (Table 1) shows that coastal current dynamics can contribute significantly to the water level above the chosen noise level of 2 cm. Corrections to z_H were explored by subtracting z_{NCC}-10 cm, delayed by 0, 1, 2, 3 and 4 months to account for possible time of travel from the Skagerrak to Lofoten. All of these sets gave a larger standard deviation between observed and computed Q than z_H without this adjustment. It is therefore concluded that the signals from the Skagerrak are dissipated before the outflow reaches Lofoten. This may be due to the fact that much of the variable flow creates large eddies along the west coast of Norway, some of which are entrained to the shelf slope current near Stad, and that the outflow of fresh water from central Norway adds new information to the coastal current signal. As a result, no correction is made for the Skagerrak outflow.

This is a bit surprising, considering the large volumes of brackish water coming from the Skagerrak, and gives valuable insight for modeling the coastal current in regional oceanographic models of Northern Norway. Clearly, more local data is needed to evaluate the "noise" of the coastal current dynamics on z_H.

The data from Table 1 are plotted in Fig. 3 together with the geostrophic algorithm (7). The general trend is good. The theory predicts 6 % too large values, on the average, and the standard deviation of the data is 15 %. This means that the water level data from Harstad is at least as good as that for Andenes in spite of (or perhaps because of) the fact that it lies in a fjord farther from the shelf break. The fact that the average value of the algorithm calibrated at Stad is 6% higher than the computed data from Shetland is most likely due to an additional transport from the East Icelandic Current (EIC in Fig. 1) and the NCC.


Q NAC at Shetland (Gould et al, 1985)
Q NAC at Stad (Mysak+ Schott ,1977)
Geostrophic algorithm (eq.7):
g'=0.005 m/s 2
f =1.35 x 10 -4 s -1
H =450 m
Q BC = 5/3 Q BT
0.6
0.4
0.2
0
ζ ,m
Sea at rest
5
10
Q,Sv

COMPARISON WITH EVENTS OF 1982 - 1984

There are several other types of data available from the period of water level measurements shown in Table 1. A few of them will be discussed in terms of Q computed from (7), recalling that this relation, on the average, gives a 6% higher value than the transport at Shetland. The results for the entire period from September 1982 to August 1984 are plotted in Fig. 4. Extreme changes from month to month are apparent. The field data from Lofoten will be commented later.

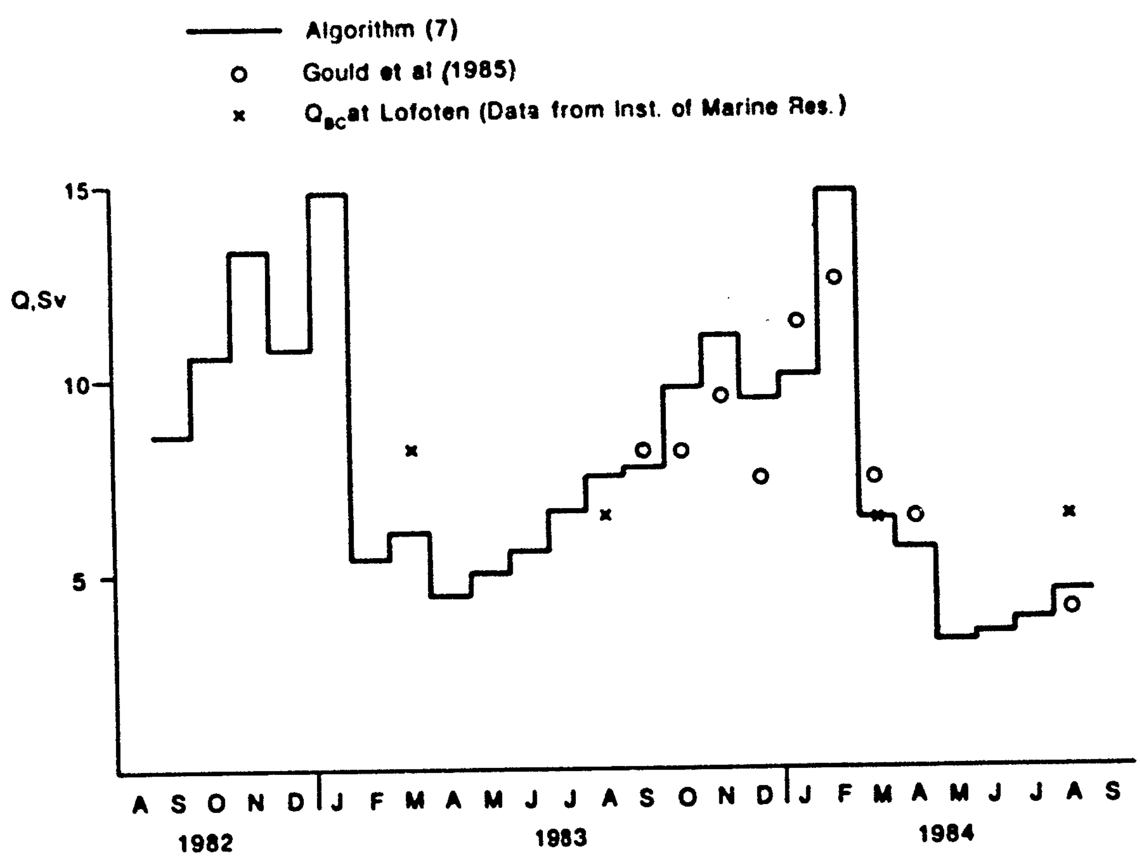


Fig. 4. Computed monthly inflow of Atlantic Water to the Norwegian Sea. O - Q past Shetland (GOULD et al. 1985). X - Q_{sc} from 2-day hydrographic surveys at Gimsøy (Institute of Marine Research).

Barotropic currents near Shetland - The CONSLEX program (GOULD, 1982) contains direct current measurements along the continental shelf north and west of Shetland prior to the intensive transport calculations of GOULD et al. (1985). The mooring net was sparse and there was really only one station that was located in the barotropic shelf slope current at the 500 m isobath along the Greenwich meridian. The (barotropic) transports estimated from this mooring are compared with the computed monthly values for the algorithm ($Q_{BT} = 3/8\ Q$) in Table 3.

Table 3. Comparison of computed and observed shelf slope currents $Q_{BT} = 3/8\ Q$. (CONSLEX data analyzed by JACOBSON & LICATA, 1985)

Year	Month	Q_{BT} observed (Sv)	Q_{BT} computed (Sv)
1982	Oct	4.0	3.9
	Nov	3.8	5.0
	Dec	2.4	4.0
1983	Jan	4.0	5.6
	Feb	2.1	2.0
	Mar	2.3	2.3

The results show that the transports estimated by the single mooring are on the average 18 % lower than the estimates by the theory, however, the trends seem to be reasonably well represented in the water level measurements at Harstad with a standard deviation of 27 %.

Onshore currents in the Norwegian Trench - JACOBSON & LICATA (1985) compared the CONSLEX data to field measurements at the Troll Field to obtain a predictor for the undercurrents regulating the high speed eddy currents near the surface. In Fig. 5 the monthly average onshore current is plotted together with the estimates of Q_{BT} from the water level measurements from Harstad (eq. 7).

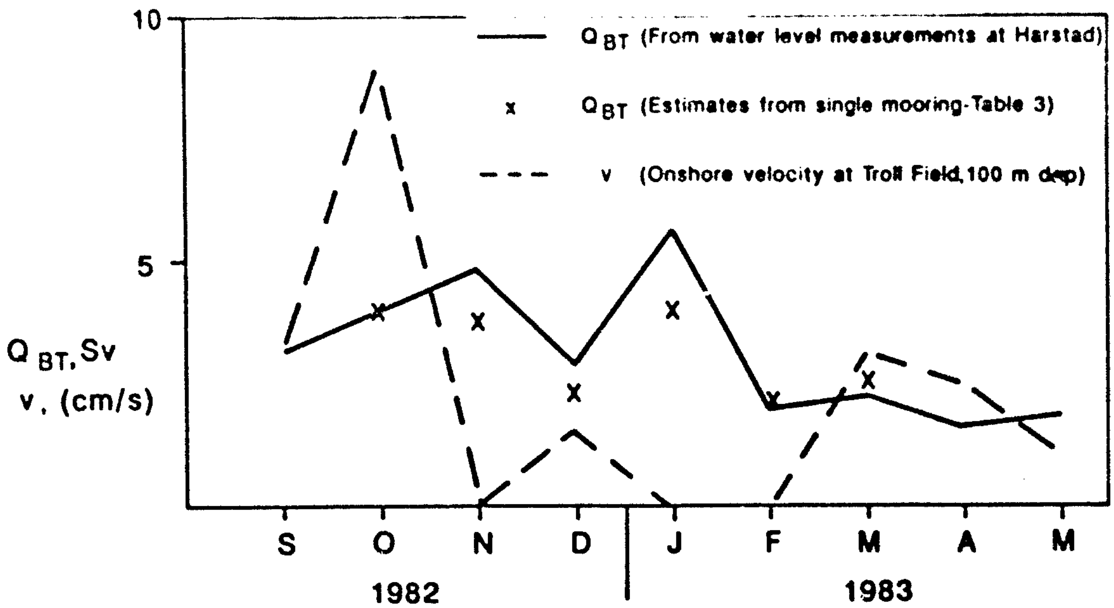


Fig. 5. Comparison of the barotropic shelf break flow and onshore currents at the Troll Field.

This data set shows large discrepancies which have to be resolved both in terms of data quality, interpretation and cause/effect relationships.

Purging of the Barents Sea - MIDTTUN & LOENG (1987) showed that a large volume of dense bottom water, which had accumulated in the eastern Barents Sea over a few years, was flushed out some time between September 1982 and September 1983 (summer cruises). The exceptionally large inflow from October 1982 to January 1983 implies that the purging probably occurred at this time.

A finer resolution data set for this area is available from the monthly ice cover presented by PARKINSON & CAVALIERI (1989). The details of the total ice cover of the Barents and Kara seas are reproduced in Fig. 6. The summer cruises mentioned above were made in September when the ice cover is at a minimum. The most interesting features from Fig. 6, however, are the relatively low values of ice cover during the winters of 1982 and 1983 (noted by arrows) implying purging. There appears to be a direct correlation between the reduced

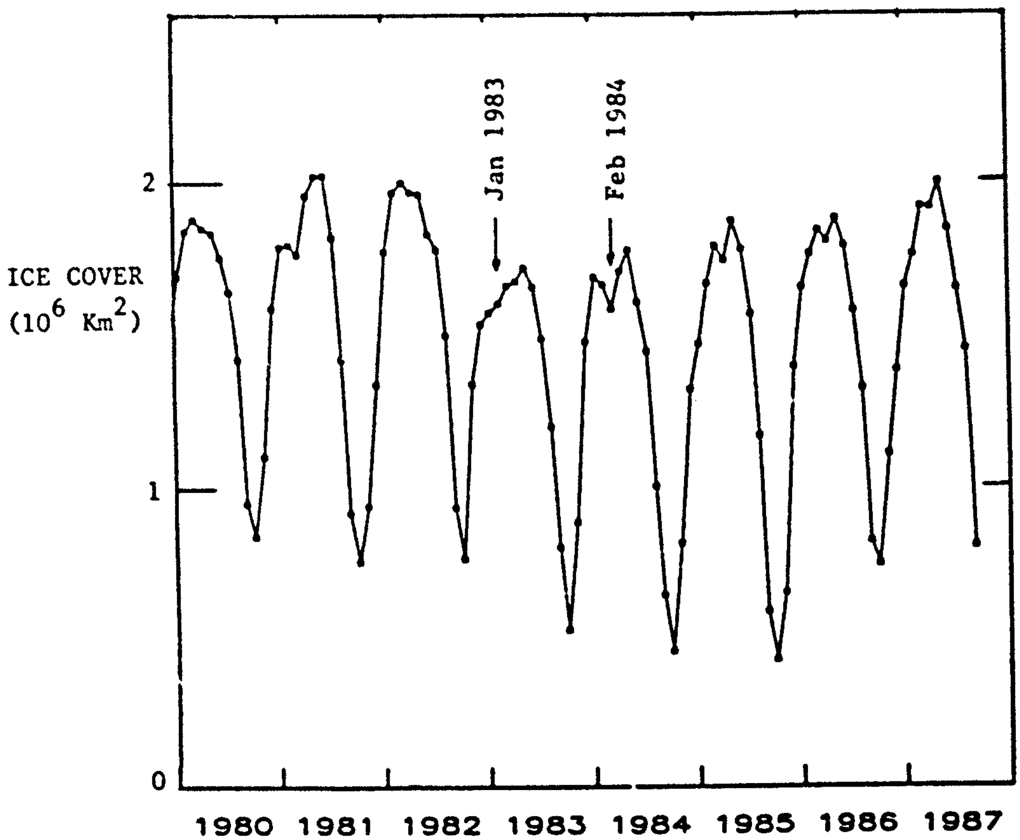


Fig. 6. Ice cover in the Barents and Kara Seas.
(Adapted from PARKINSON & CAVALIERI, 1989).

Comparison with off-shelf hydrography at Gimsøy - Several years of hydrographic data NW of Lofoten were made available by the Institute of Marine Research, Bergen (the Gimsøy section). The off-shelf stations beyond the 1000 m isobath were used to compute the potential energy of the upper layer and the baroclinic transport of the NAC using (1). The relevant data for Q_{BC} are noted by x in Fig. 4.

According to the algorithm, these results are only 5/8 of the total transport. These data, each obtained during a period of two days, show much scatter and are not representative of the monthly averages. An analysis of 17 sections for the period 1978-1984, taking into account the seasonal variations, indicates a total annual inflow past Lofoten of 9.2 Sv. It was shown that the Stad section gives a 6 % larger Q than the Shetland section. It is reasonable to accept that

the East Icelandic Current could provide a further increase and perhaps even increase the Q_{BC}/Q_{BT} ratio to the north.

If the assumptions leading to these computations are valid, the results imply an additional circulation of 1.2 Sv generated within the Nordic seas. According to JONSSON (1991) this is a reasonable conclusion. It is, however, difficult to interpret cause-effect relationships on the basis of correlations alone since the low-frequency wind-induced circulations in the Norwegian Sea and the North Atlantic are driven by the same synoptic weather system.

DISCUSSION AND CONCLUSIONS (WHERE DO WE GO FROM HERE?)

The geostrophic algorithm of (7) seems to capture many of the features of monthly variability in the inflow of Atlantic Water to the Norwegian Sea and its consequences. This is an important process for life both on land and in the sea, and its variability is important for modelling the regional circulation on the Norwegian Continental Shelf. The analysis shows that the Harstad tide gauge is a useful station for monitoring the NAC, giving a standard deviation of 15% from 9 months of transport measurements. This result begins to approach the noise level of $\pm 8\%$ inherent in the exclusion of processes giving less than 2 cm monthly variability. Much of the remaining noise may lie within the coastal current dynamics near Lofoten.

These first comparisons with readily available data are encouraging enough to expand the effort to include:

1. longer time series (the length of the water level records at Harstad),

2. a more thorough analysis of the coastal current dynamics near Harstad,

3. more exhaustive and systematic tests with all data sets available,

4. the extension of the technique to fortnightly averages

5. an analysis of cause/effect relationships to test the validity of the assumptions and to improve our understanding of the synoptic/global aspects of the variability (how does cooling and freezing pull the warm water through the basin?).

These goals will require a more precise and detailed analysis of the data presented here and will require additional information from other sources.

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